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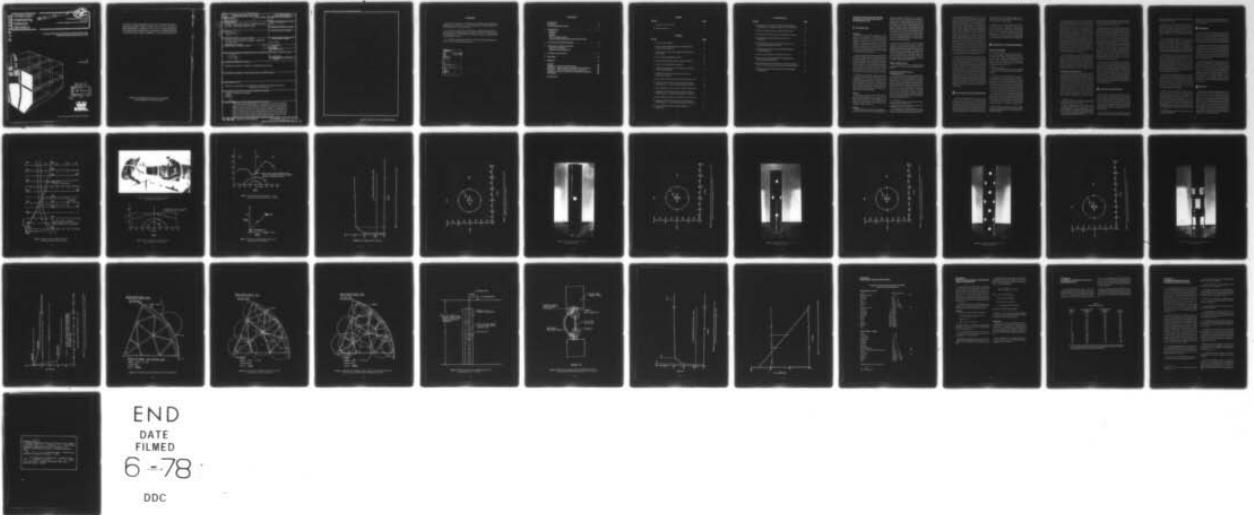
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CATHODIC PROTECTION DESIGN FOR BRACKISH WATER SYSTEMS: FRESH WA--ETC.(U)  
MAY 78 F W KEARNEY

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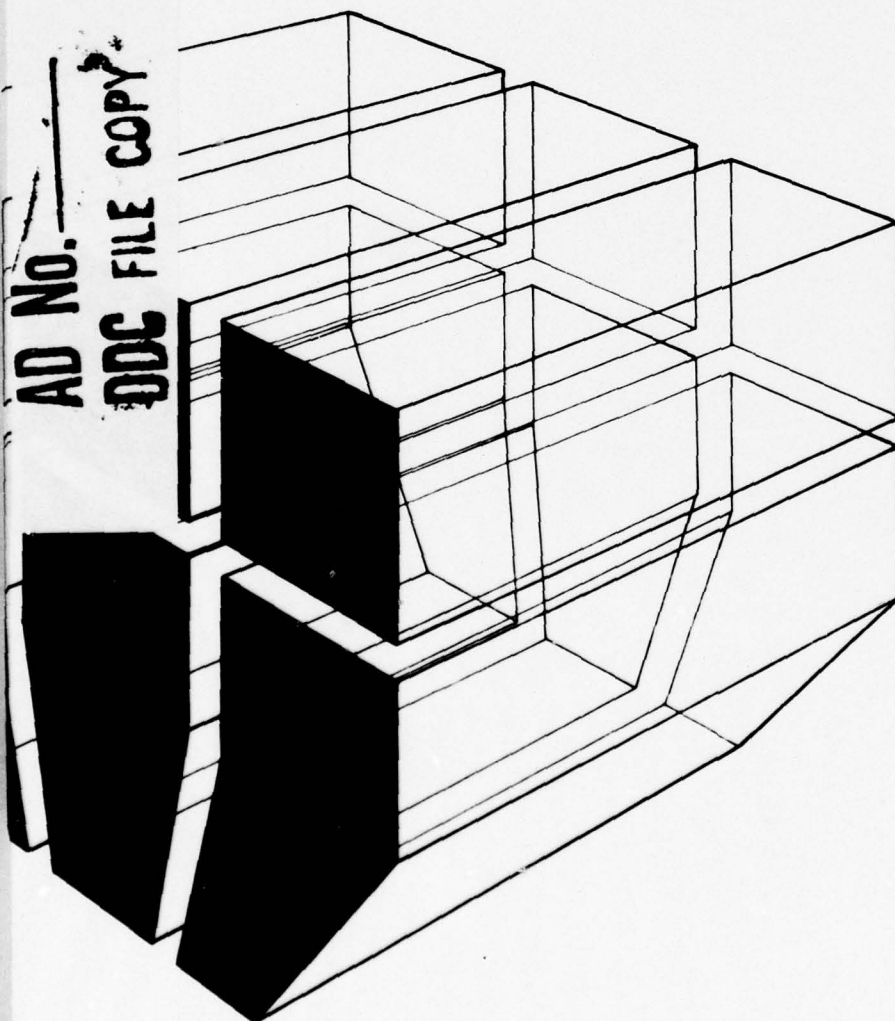
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May 1978

Corrosion Mitigation in Civil Works Projects

CATHODIC PROTECTION DESIGN FOR BRACKISH WATER  
SYSTEMS: FRESH WATER BAYOU LOCK



by  
F. W. Kearney

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## FOREWORD

This study was conducted for the Directorate of Civil Works, Office of the Chief of Engineers (OCE), under CWIS 31204, "Corrosion Mitigation in Civil Works Projects." The OCE Technical Monitor was Mr. J. Robertson.

The research was conducted by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (CERL). Mr. F. Kearney was the Principal Investigator. Mr. W. Mattheessen of CERL, who made the electric field plots, also participated in the study.

Dr. G. R. Williamson is Chief of EM. COL J. E. Hays is Commander and Director of CERL, and Dr. L. R. Shaffer is Technical Director.

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# CATHODIC PROTECTION DESIGN FOR BRACKISH WATER SYSTEMS: FRESH WATER BAYOU LOCK

## 1 INTRODUCTION

### Background

While the theory of cathodic protection (CP) is well understood, its application to mitigating corrosion damage of actual structures can be quite difficult and complicated. Application of CP theory is particularly difficult for hydraulic structures used by the Corps of Engineers in navigational lock systems, because such factors as irregular structure shape, proximity to other structures, and variable water velocity must be considered. Barges and floating debris can also cause damage to anode installations on waterways.

Another environmental condition affecting CP design for these structures is the water conductivity. Since the protection provided to the structure depends on electrical current densities, which are partially determined by water conductivity, that conductivity is a significant design parameter. For most inland systems, only fresh-water is involved, and the slight conductivity variations are accommodated in most cases. For coastal systems subject to saltwater "intrusion," however, the conductivity variation is extreme: from fresh water to seawater.

In addition to the consideration which must be given to the above-described factors in anode selection and configuration for a CP system, meticulous care must be taken in designing the ancillary components of the system. Because of the dynamics of the lock gates, anode installation requirements are more stringent than they are for passive structures; the saltwater spray condition imposes severe constraints on any electrical fixtures associated with the CP design.

### Objective

The objective of this study was to develop cathodic protection design guidelines for sector gates that will insure effective, long-term corrosion mitigation in conditions of extreme variations of water conductivity and moderate to severe stochastic loads induced by gate movement, turbulence, debris, etc.

### Approach

Design guidelines were developed by using results of previous U.S. Army Construction Engineering Research

Laboratory (CERL) cathodic protection research to design a CP system for a hydraulic structure subject to the operational conditions listed above. The structure selected as most typical for this program was the Fresh Water Bayou Lock in the Intracoastal Waterway System, New Orleans District, Lower Mississippi Valley Division. Cathodic protection impressed-current was previously used in this structure with less than satisfactory results because of poor anode installation and deterioration of the electrical system from saltwater spray. A brief but enlightening history of the nature and effects of the hostile aspects of this structure-environment situation was therefore available.

Design parameters for the structure were determined (Chapter 2). The operating characteristics of cathodic protection systems under these conditions were established experimentally and a design facilitating anode replacement was developed (Chapter 3). Electric field analysis was then performed to determine whether various anode configurations would provide adequate protective voltage at the structure (Chapter 4). Results of the various evaluations were then combined to formulate specific design guidelines (Chapter 5).

### Mode of Technology Transfer

This study will impact Corps of Engineers Guide Specification CE 1508<sup>1</sup> and Technical Manual (TM) 5-811-4.<sup>2</sup>

### Types of Cathodic Protection Systems and Protection Criteria

The two basic types of cathodic protection systems are the sacrificial anode and impressed-current types. The former uses an anode material that is inherently anodic (active) to the components to be protected; the structure is thus made the cathode of a galvanic couple. In an impressed-current system, positive current is delivered to the structure through the electrolyte by an external direct current power supply in conjunction with a system of inert anodes. In either case, the metal to be protected is polarized in the passive or negative direction, and its corrosion rate is consequently reduced. For a more detailed discussion of CP for civil works, see CERL Interim Report M-222.<sup>3</sup>

<sup>1</sup>Cathodic Protection System for Lock Miter Gates, CE 1508 (Office of the Chief of Engineers, 1967).

<sup>2</sup>Engineering and Design: Corrosion Control, TM 5-811-4 (Department of the Army, 1 August 1962).

<sup>3</sup>F. W. Kearney, *Corrosion Control in Civil Works: Cathodic Protection*, Interim Report M-222/ADA045184 (U.S. Army Construction Engineering Research Laboratory, July 1977).

The advantages and disadvantages of the two types of systems must be weighed during the selection process. For low-resistivity environments, such as seawater, the relatively low driving force or voltage available from a sacrificial system (usually less than 1 V for steel structures) is in many cases adequate. In higher resistance media, however, voltage or IR drop through the electrolyte is often a limiting factor. Sacrificial magnesium anodes, which are about 1 V negative to steel and 0.5 V active to either aluminum or zinc anodes, have been satisfactorily employed in fresh waters; however, the higher voltages available with impressed-current cathodic protection are often necessary. For this reason, the latter type of system is more often employed for fresh-water hydraulic structures. Environment conductivity in the immediate vicinity of anodes is particularly important, since it is here that a significant fraction of the total circuit resistance occurs. Some structures do not lend themselves to the use of impressed-current systems, i.e., tractor gates. Also, a combination of both types of systems may yield the lowest overall annual cost.

Several criteria exist as to what constitutes protection for various corrosion situations where cathodic protection is employed. The most widely referenced criterion, which is particularly applicable to coated hydraulic structures, requires that the steel surface be polarized to  $-0.85$  V relative to a copper-copper sulfate ( $\text{Cu}/\text{CuSO}_4$ ) reference cell. To accomplish this, a certain current density must be delivered through the electrolyte to the structure. In seawater, a current density for coated steel of about  $2 \text{ mA/sq ft}$  ( $11.11 \text{ mA/m}^2$ ) is generally necessary for cathodic protection. Careful determination of the proper current density is important, since excessively negative potentials on coated steel surfaces often result in gas evolution of the metal-coating interface and "blistering" of the paint. The protective properties of the coating can thereby be significantly compromised.

## 2 COLLATION OF DESIGN PARAMETERS

The New Orleans District forwarded random samples of canal water to CERL from April through August 1976. Figure 1 shows the locations at the lock where samples were taken. The constituents in these samples were determined in order to prevent discrepancies between laboratory tests and field conditions caused by spurious compounds that would change the basic electrochemical conditions. No such material was detected.

Appendix A presents the complete qualitative spectrochemical analysis and concentration estimates of the constituents of one of these samples.

Discussions with New Orleans District personnel indicated that low water conditions prevail near the lock and the salinity was consequently on the high side. Since it was also indicated that conditions of low salinity could occur, it was necessary to determine the operating characteristics of cathodic protection systems under these circumstances and to determine a practical design to provide protection between the dewatering periods.

## 3 EXPERIMENTAL DESIGN PROCEDURE

### Effects of Varying Salinity

#### *Impressed-Current System*

The obvious approach for an impressed-current design under the defined conditions was the use of an automatic control rectifier. Two such units\* were tested over the range of salinity anticipated (Figure 2). As Figure 2 shows, the variation in salinity and hence in conductivity is well within the automatic control and compensation ranges of both units.

#### *Sacrificial Anode System*

Experimental investigation of a galvanic or sacrificial system for the defined conditions was somewhat more complex.

CERL uses electrolyte tanks (Figure 3) in its corrosion mitigation and cathodic protection research to measure the interaction and interdependence of various parameters, such as electrolyte salinity and anode geometry. Since the essential element of cathodic protection is an external current source that will oppose the corrosion potential of the metal to be protected at every point of the exposed surface (where there is a holiday in the paint coating), the CP design must insure that the protecting potential is maintained despite changes in structural geometry. To accomplish this, a design approach based on the continuum aspects of the anode electric field and the associated current distribution is used. Examples of the many field plots made using this technique during this investigation for various conductivities, geometries, etc., are shown in Figures 4 and 5.

\*The two units differed in the transfer mode of the feedback signal from the reference half cell; unit "R" used a continuous feedback voltage signal, while unit "H" used a pulsed or interrupted feedback signal.



A sacrificial anode has an electric field gradient whose value depends on both the anode material itself\* and the conductivity of the medium in which the anode is immersed. The geometry of the resultant electric field depends on the geometry of the boundaries. The distance at which a certain specified voltage occurs is defined as the "throwing power" of that anode/electrolyte combination. To determine the effect of variable salinity on the "throwing power" of an anode, a zinc anode was suspended in the electrolyte tank at a distance of 2.8 ft (0.86 m) from the intersection of two mild steel plates (Figure 6). Sodium chloride was added to the water in the electrolyte tanks to obtain different degrees of salinity; an interval of time was allowed between additions to allow the polarization voltage to stabilize. The voltage at the point of intersection was monitored with silver-silver chloride reference electrode.<sup>†</sup> Figure 7 gives the results of this test.

For the most probable conductivity variation in the water at the Fresh Water Bayou Lock, the voltage provided by a zinc sacrificial anode system would provide an adequate protective voltage for a concentration as low as 0.1 percent sodium chloride. Based on the experimental results, the worst condition (lowest conductivity) was defined as 0.1 percent sodium chloride. Subsequent testing was done at this concentration level.

#### Facilitation of Anode Replacement

Since anodes on hydraulic structures are subjected to mechanical stresses, design must facilitate anode replacement if depletion occurs before a scheduled major maintenance activity. Some type of protective structure around each anode would also be indicated. The most obvious and practical protective structure would be a simple circular tube of nonconducting material rugged enough to withstand conditions to which it will be subjected. Such a tubular protective system would also provide a permanent guide for raising and lowering a string of "sausage" anodes. Obviously, the protective tubes would require apertures to permit CP current flow. As the area of these apertures increased, however,

the protective value of the tubes would decrease due to mechanical weakening. Therefore, an electrical-mechanical optimization must be established.

To determine the effect of aperture size on the resultant electric field, a series of plots was made in a 0.1 percent salt electrolyte. The field associated with a bare zinc anode is shown in Figure 8; a value of 0.917 to 0.919 V is obtained at a radius of 1 ft (0.3 m) from the anode. Holes were drilled in a 4-in. (102-mm) diameter plastic pipe to remove 1 percent of the pipe's surface area; a section of this tube is shown in Figure 9. The drilled pipe was used with a 2 in. × 2 in. (51 mm × 51 mm) zinc anode. The resultant field plot is given in Figure 10; a voltage of 0.791 to 0.792 was obtained at a 1-ft (0.3-m) radius. Figures 11 through 16 show drilled pipes and their respective field plots for surface area removals of 3.5, 6.7, and 26 percent. As shown in Figure 16, when 26 percent of the surface area is removed, the field is 0.904 to 0.906 V at a 1-ft (0.3 m) radius. This value is 10 to 12 mV below the value obtained with an unprotected anode.

The current flow in the sacrificial system would also be affected by the size of the aperture in the protective structure. As the exposed area increased, the current would also increase until it reached the limiting value with the entire anode exposed (Figure 17). The current value at 26 percent exposure is 9.1 mA compared to the 9.6 mA obtained with the unprotected anode. The voltage plot for a 1-ft (0.3-m) radius is also included on this curve. As shown, the curve becomes asymptotic at about a 25 percent area removal; this would appear to be the appropriate compromise between electrical and mechanical protection.

## 4 ELECTRIC FIELD ANALYSIS

In a practical, site-specific CP system, the only criterion of a satisfactory design is a survey of the protected structure surface using a reference half-cell to insure proper CP voltage levels. To accomplish this, the pattern of the electric field (which determines the current distribution) must be approximately constructed during the design phase. Parameters influencing the field are anode potential, electrolyte conductivity, and structure/anode geometry.

The anode potential is easily determined: for sacrificial anodes, the potential is obtained from the galvanic

\*Appendix B presents the calculations necessary to determine the total pounds of anode required to produce a given current density for a given number of years.

†Although corrosion engineers typically express corrosion potentials and cathodic protection voltage levels in terms of measurements made with a copper-copper sulfate half-cell, this type of cell cannot be used in brackish environments because of cell contamination. A silver-silver chloride half-cell was therefore used in this study. Appendix C presents data for comparing voltage obtained using various half-cells.



series; for impressed-current systems, anode potential is established by the rectifier.

The effects of electrolyte conductivity have been illustrated by the curve in Figure 7. Essentially, the conductivity determines the "protective throwing" capability of an anode at a given potential; i.e., lower resistivity gives greater "throw" distance. This is a restatement of Ohms Law for a spatial (three-dimensional) case.

Since the protective voltage value at the structure surface is the ultimate criterion for adequate CP, the structure/anode geometry must be examined in detail. Because of the numerous geometrical configurations possible in hydraulic structures, a compendium of anode/geometry vs. field patterns would be prohibitive; however, the rationale employed in this design problem should provide guidance applicable to other situations.

Figure 18 gives the "throw" distance of a zinc anode for the conditions given. This figure shows that an adequate protection voltage is obtained at 10 ft (3 m). Thus, any metal element placed within 10 ft (3 m) of the anode will be protected. This is true if the field is uniform and not perturbed by other metal obstructions (as shown by Figure 5); this is the condition for the skin side of the lock gate. Figure 19 shows anode placement on the skin side with associated "circles of protection" (10-ft [3-m] diameter).\*

Figure 20 shows anode placement with "circles of protection" for a centralized location in each compartment of the gate. To facilitate mounting of the anodes, they were relocated so as to be attached to structural members (Figure 21). To graphically verify adequate protection for these anode locations, the "circles of protection" were interposed. Figures 22 and 23 give the mounting details for the anodes.

Figures 20 and 21 show that the "circles of protection" from two or three anodes overlap, indicating a voltage contribution from each of these anodes. Although this occurs, these voltages *are not additive*; i.e., if one anode field produces a voltage level of 1.1 V at a given point and another anode field has a 1.2-V value at the same point, the resultant field measured with a half-cell will not be 2.3 V, but 1.2 V. This fact is especially significant when supplemental sacrificial anodes are being considered to augment an existing CP system;

\*The number of anodes is based on the calculation of anode requirements in Appendix B.

there is sometimes concern that anodes placed in close proximity will cause paint blisters because of overage—this is not possible.

## 5 DISCUSSION

The results of this study indicate that a sacrificial anode system would provide sufficient cathodic protection for the Fresh Water Bayou Lock. Such a system would not be significantly affected by conditions of varying conductivity which have caused serious problems with the impressed-current system previously used.

The suggested system consists of zinc anodes placed as shown in Figures 19 and 21. The exposed anodes on the skin surface would be encased in 4-in. (101-mm) diameter tubes made of a strong, nonconducting material. Approximately 25 percent of the tube's surface area would be removed. This removal would provide adequate current flow without seriously decreasing the tubes' mechanical strength.

Results also indicate that a body of water's "brackishness" can be quantified and correlated with an optimum CP method. Figure 24 shows Figure 7 with salinity zones labeled A, B, and C; the limits of these zones are set at the break points of the voltage/salinity curve for a fixed geometry (detailed in Figure 6). A logical designation for these zones would be: zone A—brackish weak; zone B—brackish moderate; zone C—brackish strong. For completeness, Figure 25 shows conductivity vs. percent salinity with these zones indicated. From these data, the guidance shown in Table 1 was formulated.

## 6 SUMMARY

This report has presented design guidance for cathodic protection systems for hydraulic structures subjected to extreme variations in water conductivity and moderate to severe loads induced by gate movement, turbulence, etc. The guidance is based on a cathodic protection system design developed for the Fresh Water Bayou Lock in the Corps' Intracoastal Waterway System. The guidance includes selection of the types of systems which can be used in waters having specific salinity ranges and procedures for determining the number of anodes required and their optimum placement. Appendix D provides rudimentary economic aspects to be considered in cathodic protection.

**Table 1**  
**Guidance for Zones A, B, and C**

<b>Zone</b>	<b>Salinity, % Sodium Chloride</b>	<b>Resistivity, ohm-cm</b>	<b>Recommended CP System</b>
A	0 - 0.1	4000-500	Impressed current CP recommended; sacrificial anode throw distance limited.
B	0.1 - 0.4	500-150	Impressed-current CP preferred; sacrificial anode acceptable.
C	0.4 - 3.5 (seawater)	150-0.01	Sacrificial anode preferred.

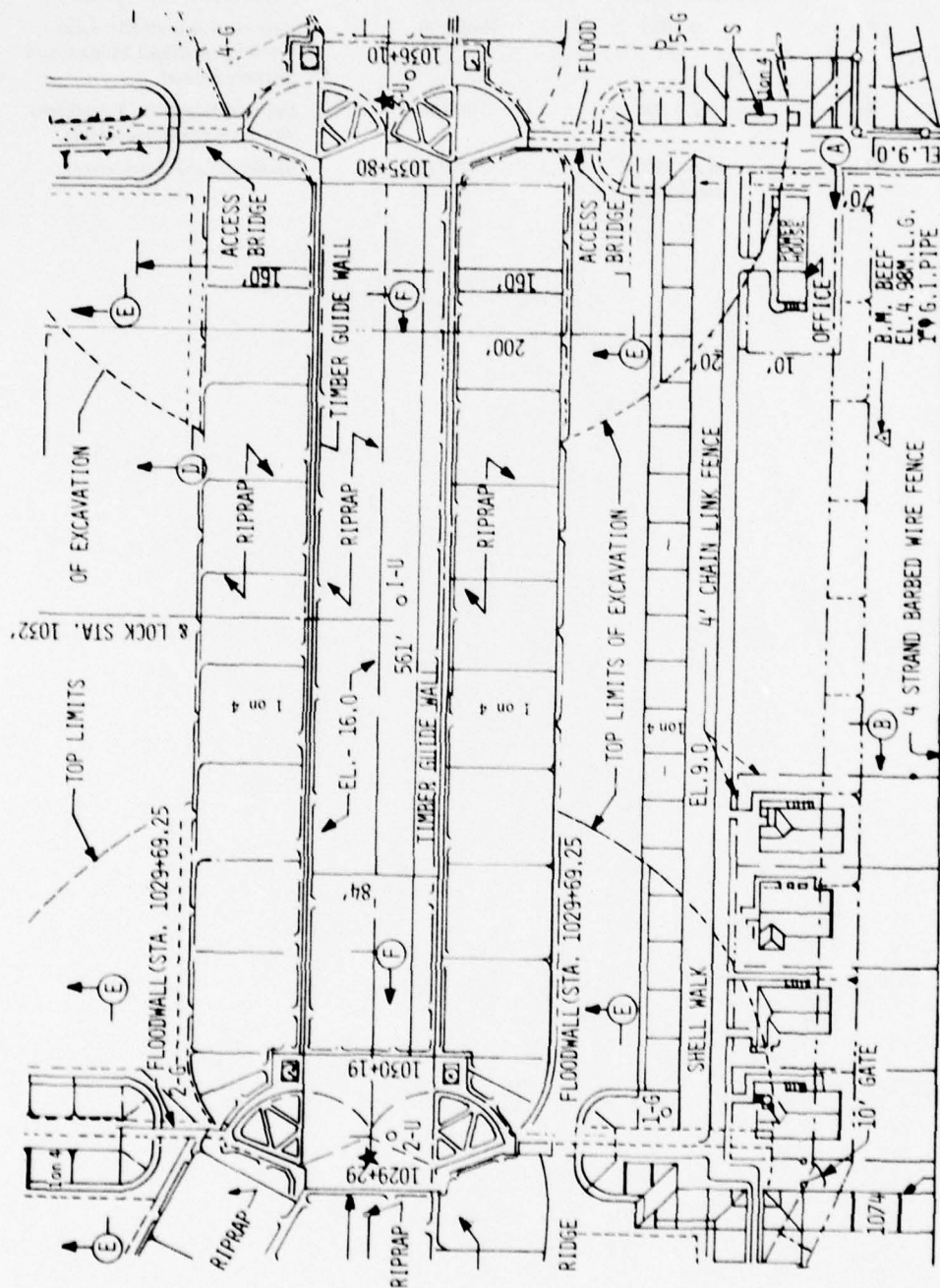


Figure 1. Location of water samples. SI conversion factor: 1 ft = 0.3048 m.

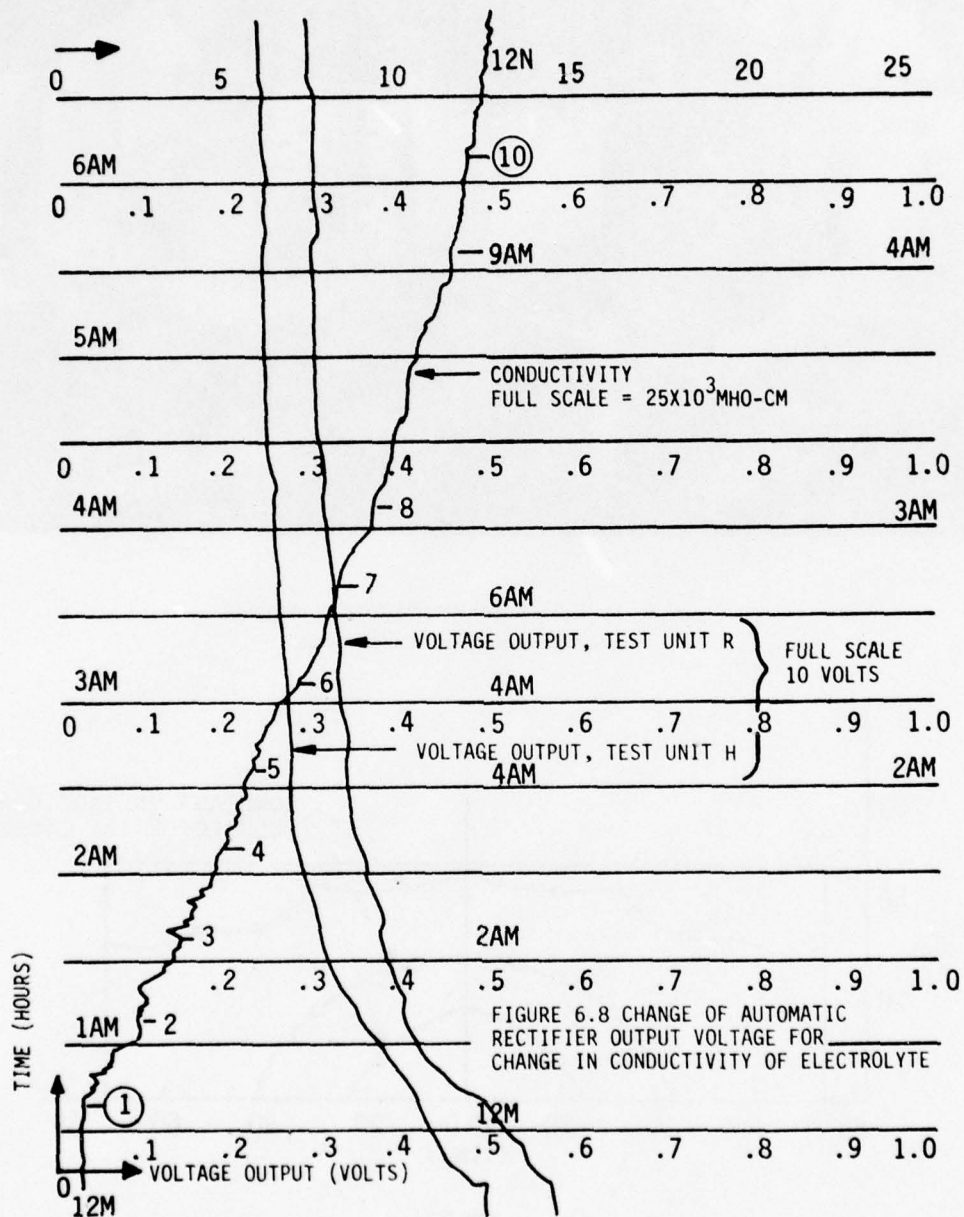


Figure 2. Change of automatic rectifier output voltage with change in conductivity of electrolyte.



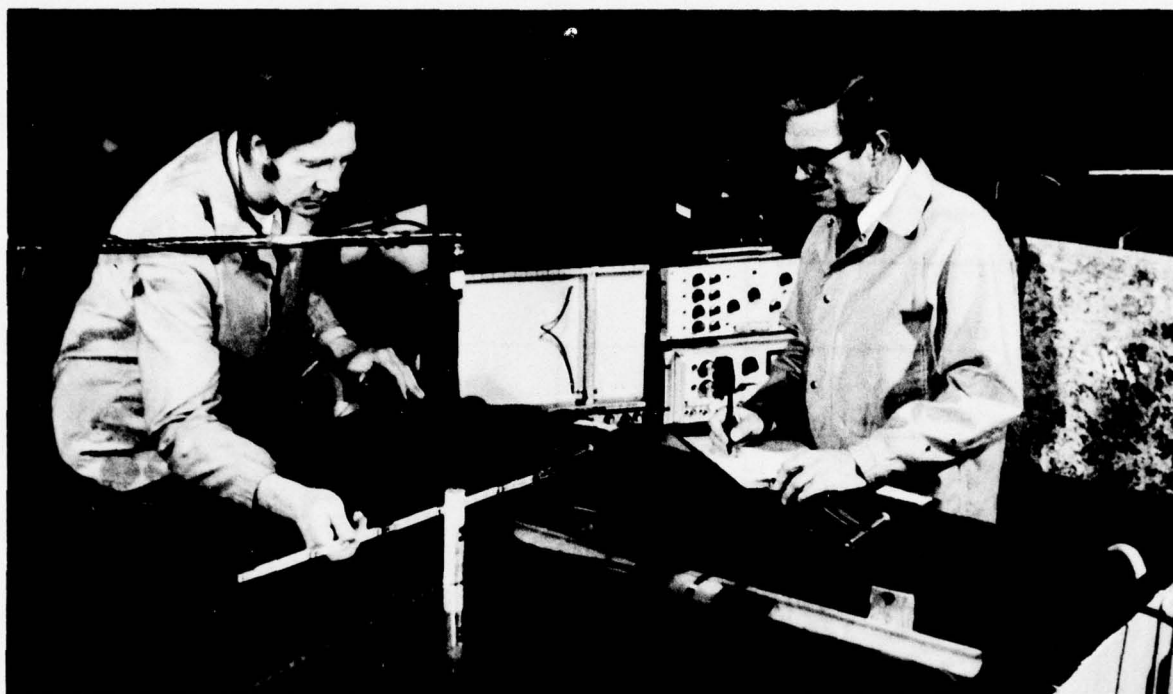


Figure 3. Typical electrolyte tank used in mapping cathodic protection electric fields.

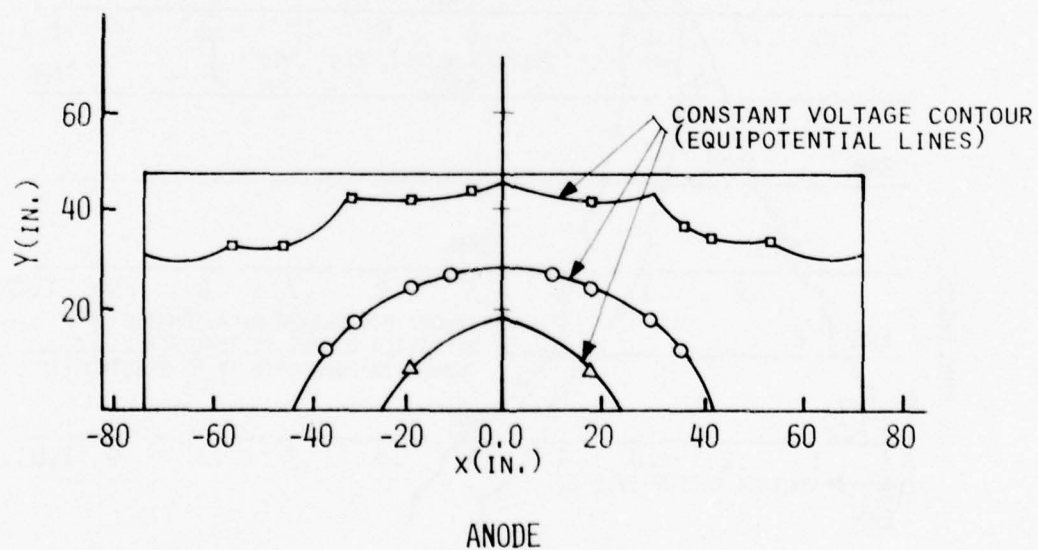


Figure 4. Electric field plot of single button anode.  
SI conversion factor: 1 in. = 25.4 mm.

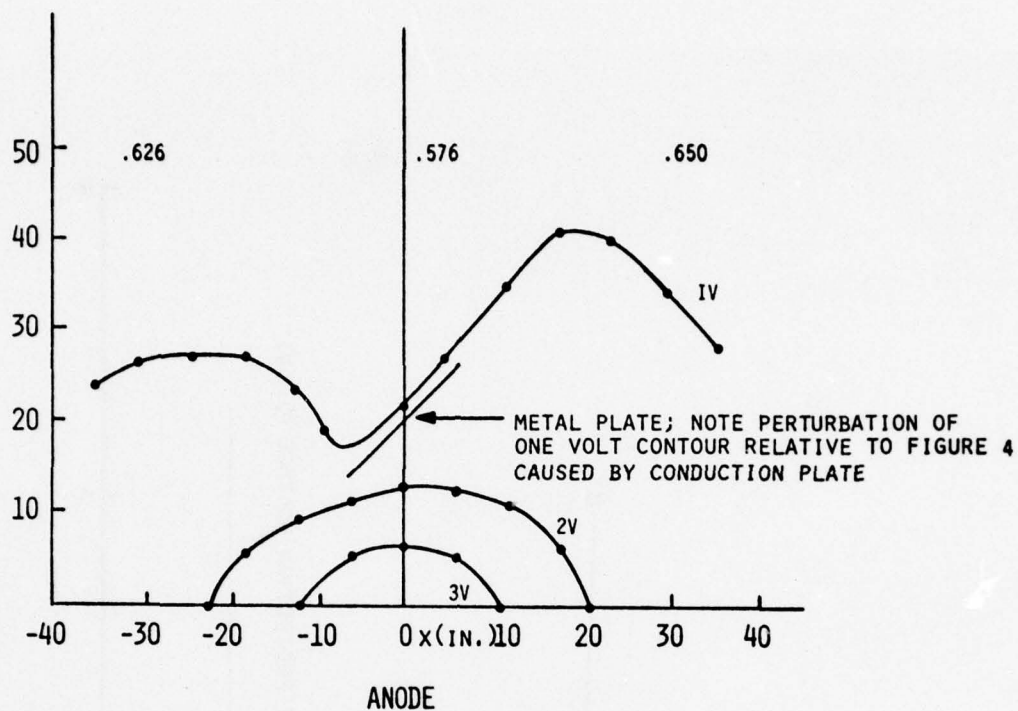


Figure 5. Electric field plot with discontinuities – anode at 45 degrees. SI conversion factor: 1 in. = 25.4 mm.

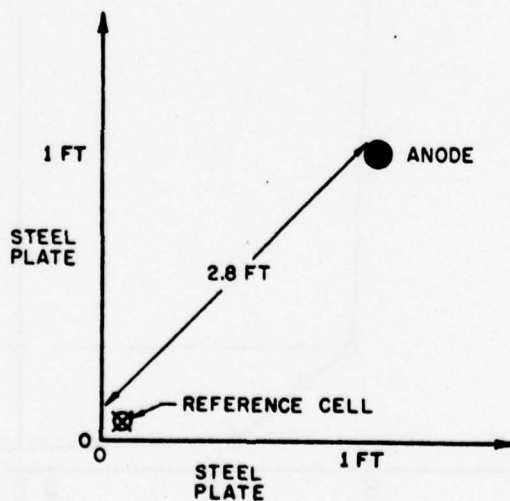


Figure 6. Geometry of "throwing power" experiment. SI conversion factor: 1 ft = 0.3048 m.

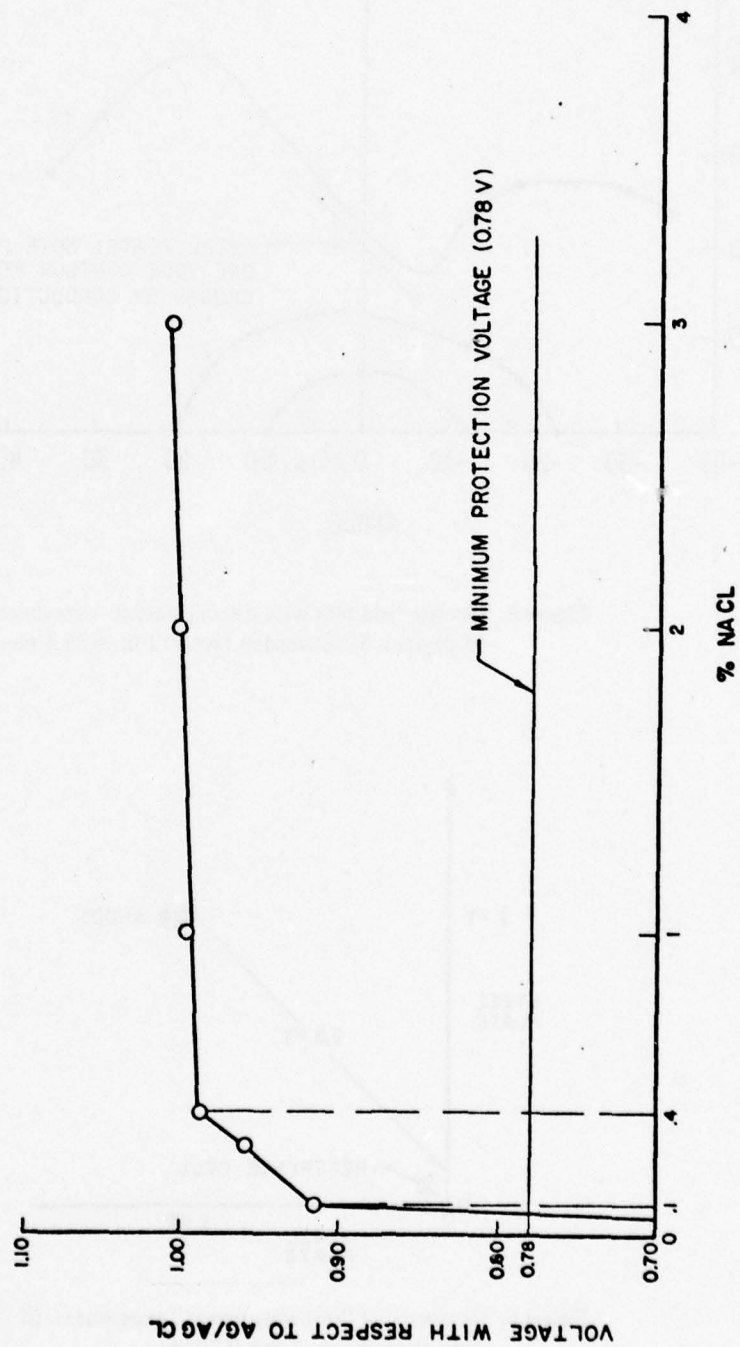


Figure 7. Voltages at intersection point 2.8 ft (0.86 m) from the anode vs. percent sodium chloride.

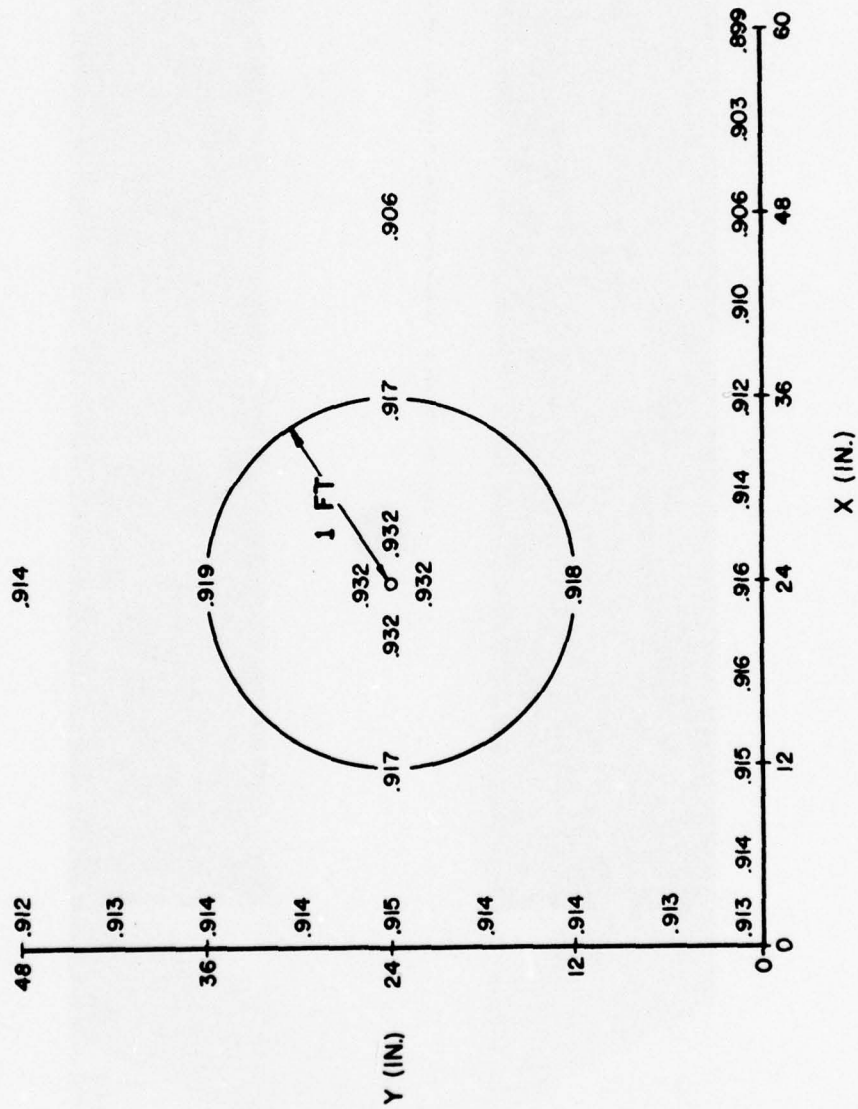
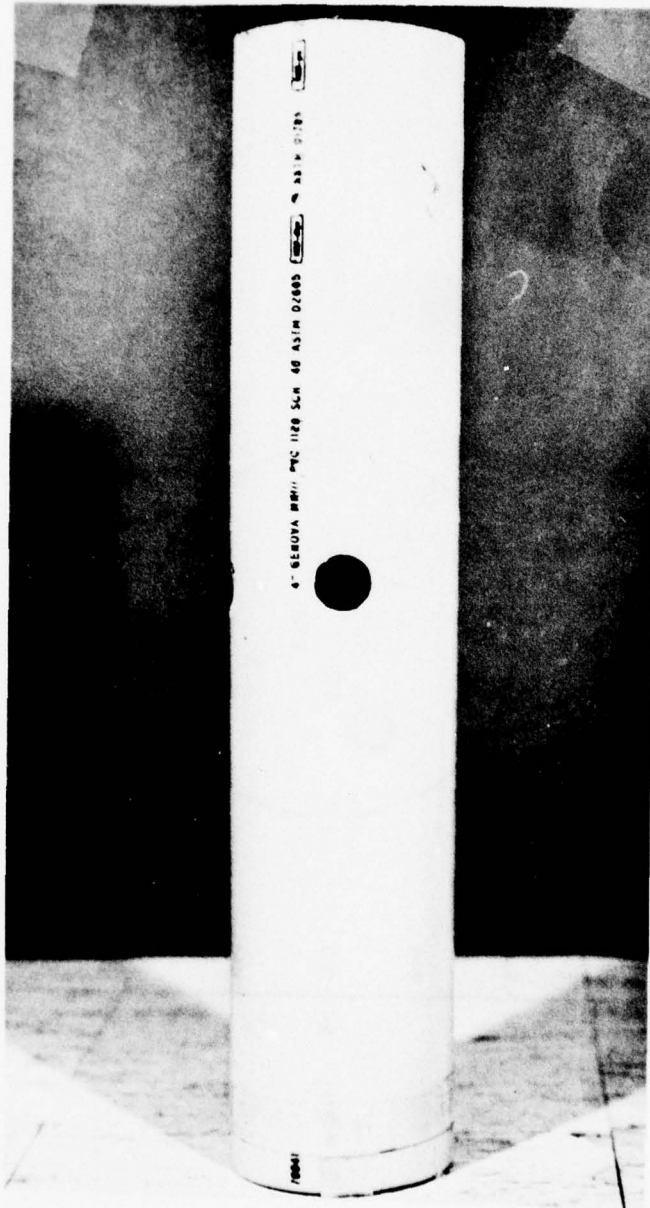


Figure 8. Voltage plot of unprotected zinc anode in a 0.1 percent sodium chloride solution. SI conversion factor: 1 in. = 25.4 mm.





**Figure 9.** Protective plastic tube with 1 percent reduction in surface area.

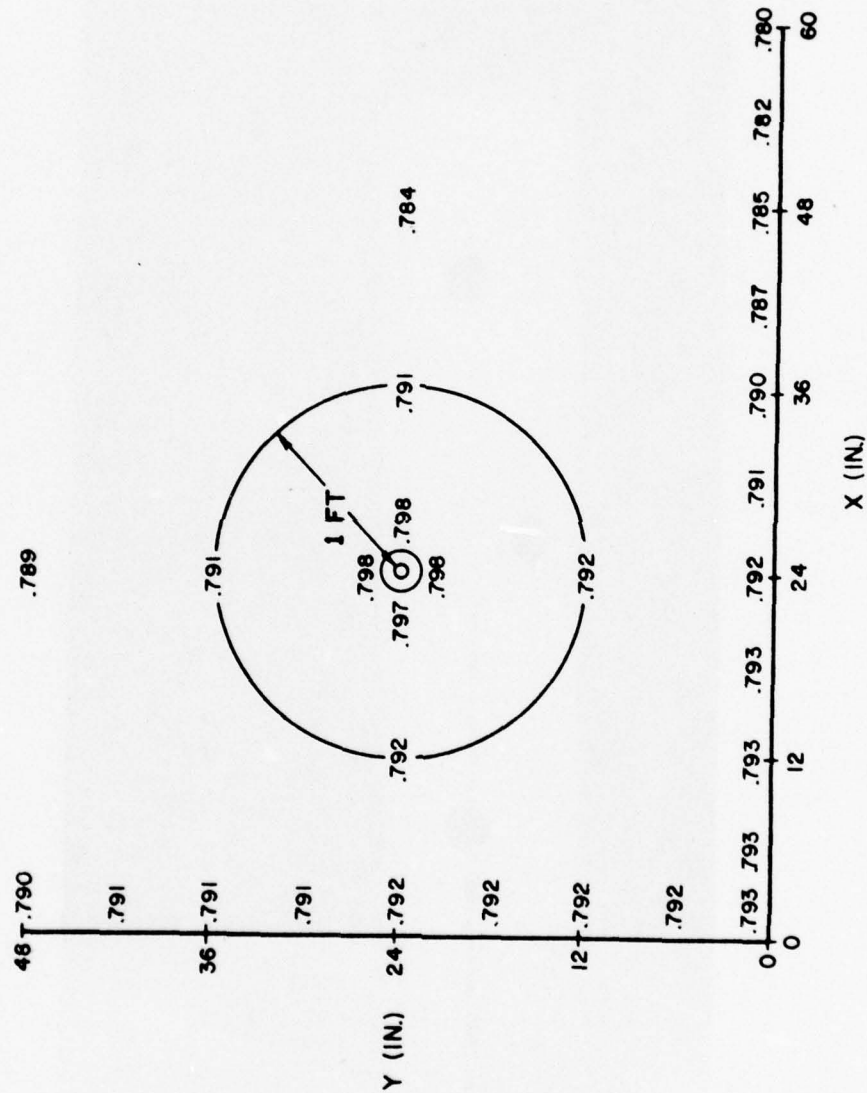


Figure 10. Voltage plot for protected zinc anode in 0.1 percent sodium chloride solution - 1.0 percent of pipe's surface area removed. SI conversion factor: 1 in. = 25.4 mm.

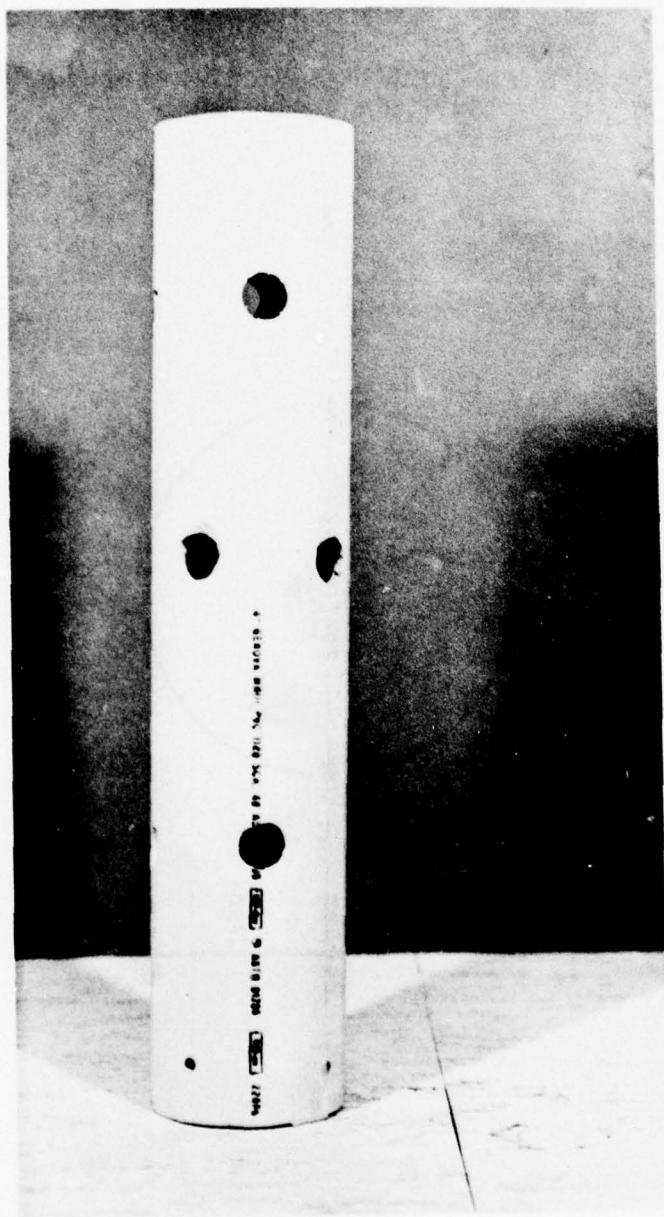


Figure 11. Protective plastic tube with 3.5 percent of surface area removed.

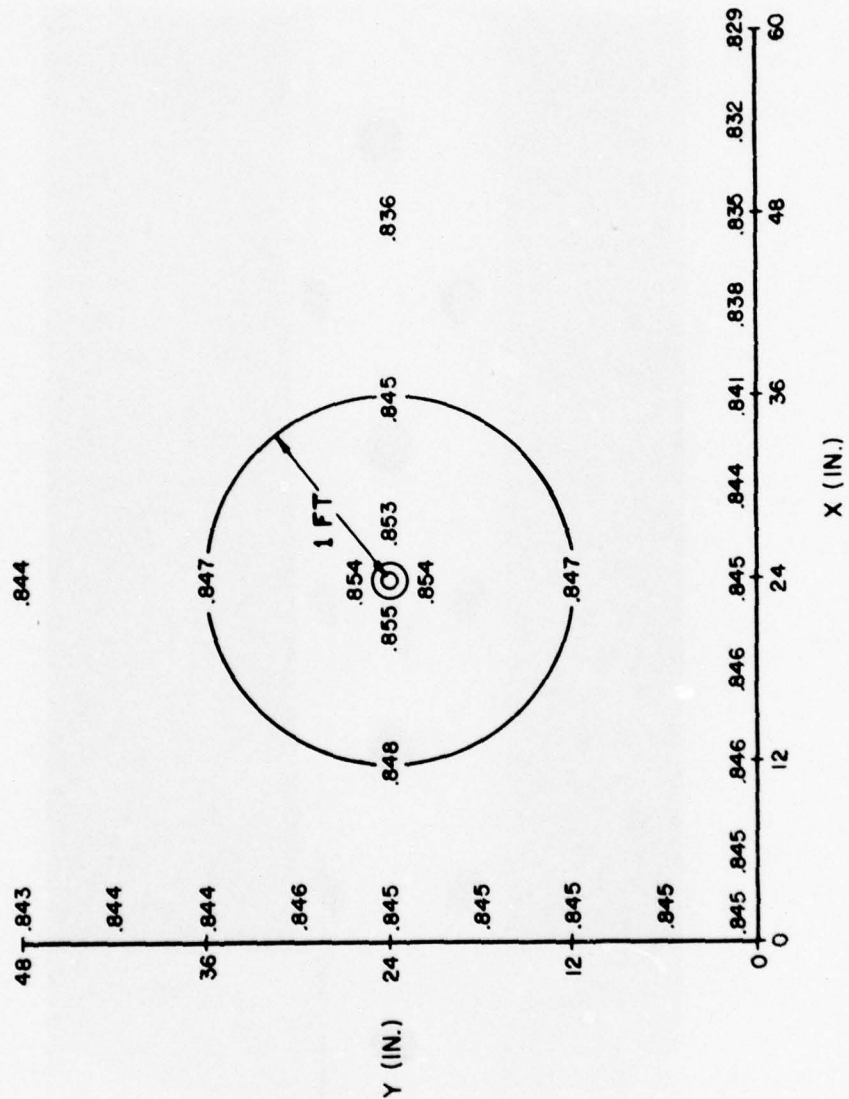
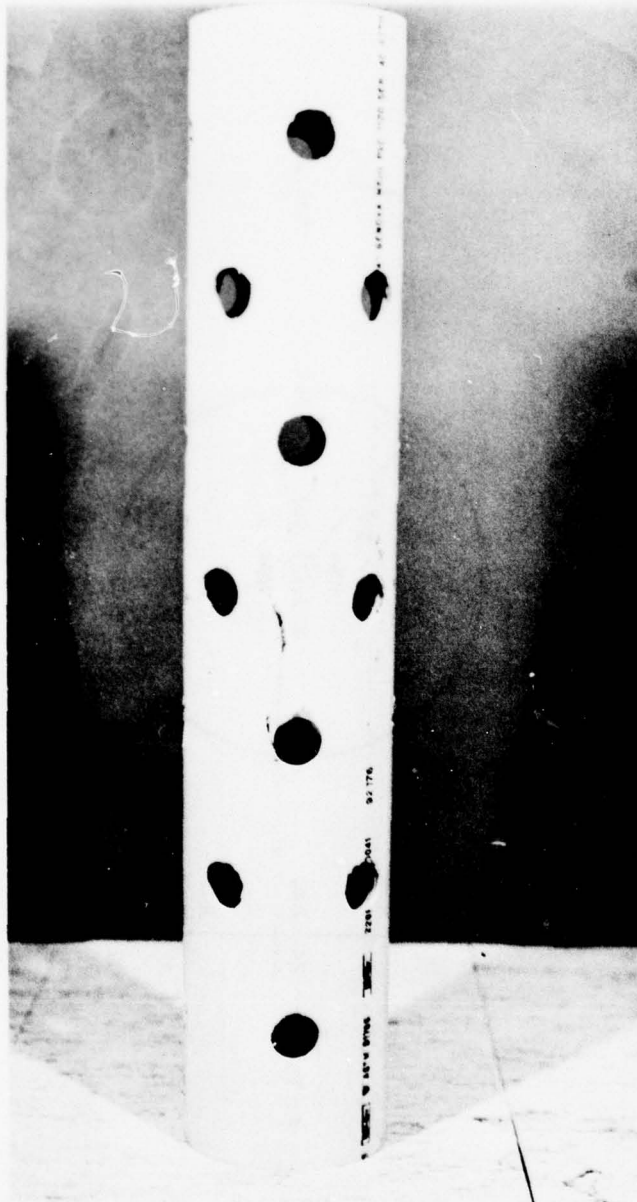


Figure 12. Voltage plot for protected zinc anode in 0.1 percent sodium chloride solution - 3.5 percent of pipe's surface area removed. SI conversion factor: 1 in. = 25.4 mm.





**Figure 13.** Protective plastic tube with 6.7 percent reduction in surface area.

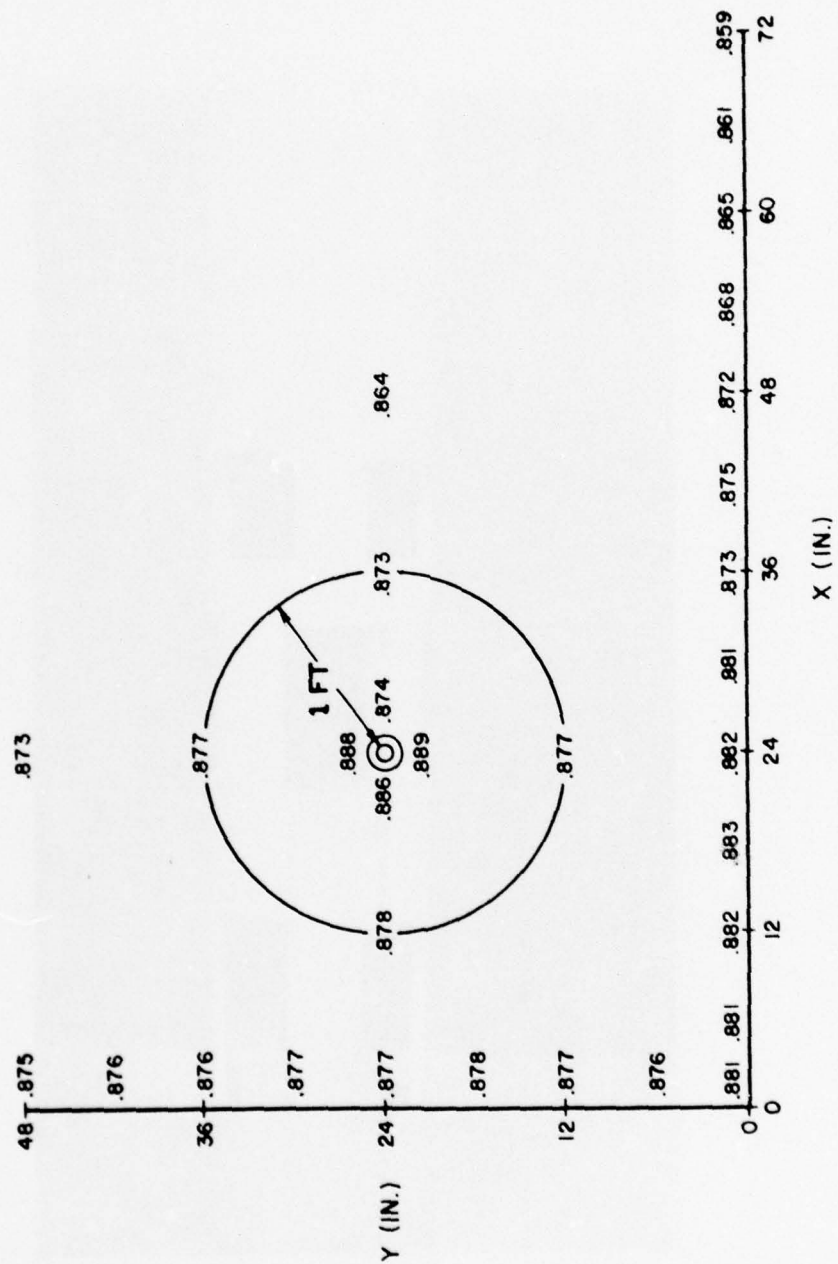


Figure 14. Voltage plot for protected zinc anode in 0.1 percent sodium chloride solution — 6.7 percent of pipe's surface area removed. SI conversion factor: 1 in. = 25.4 mm.

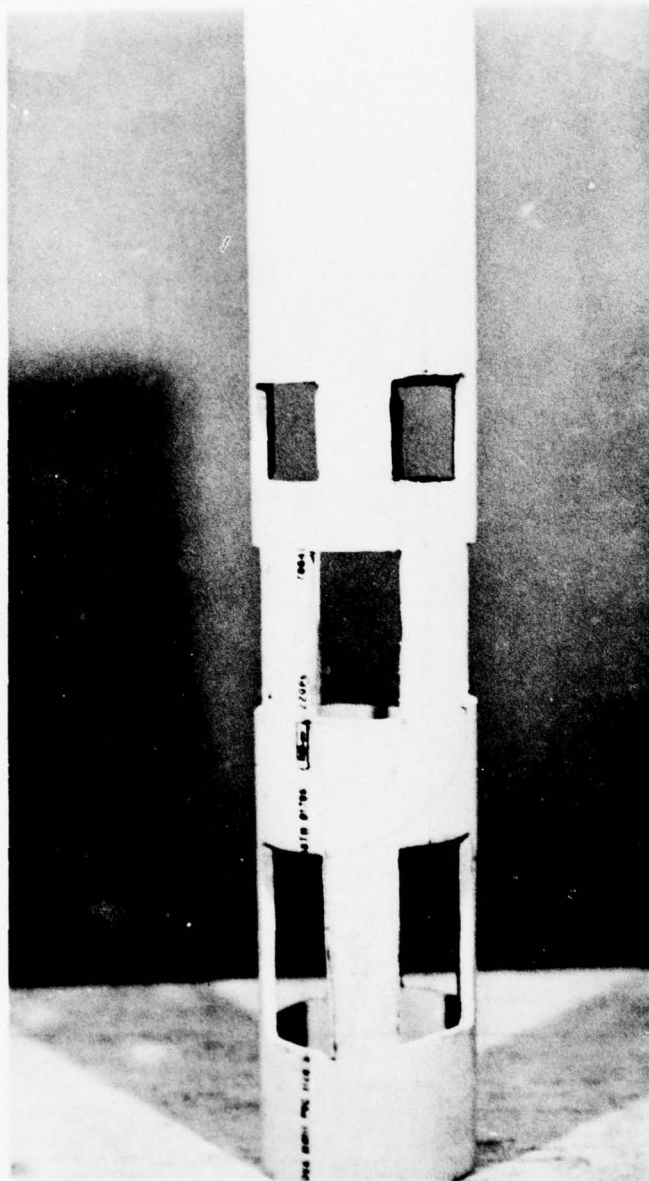
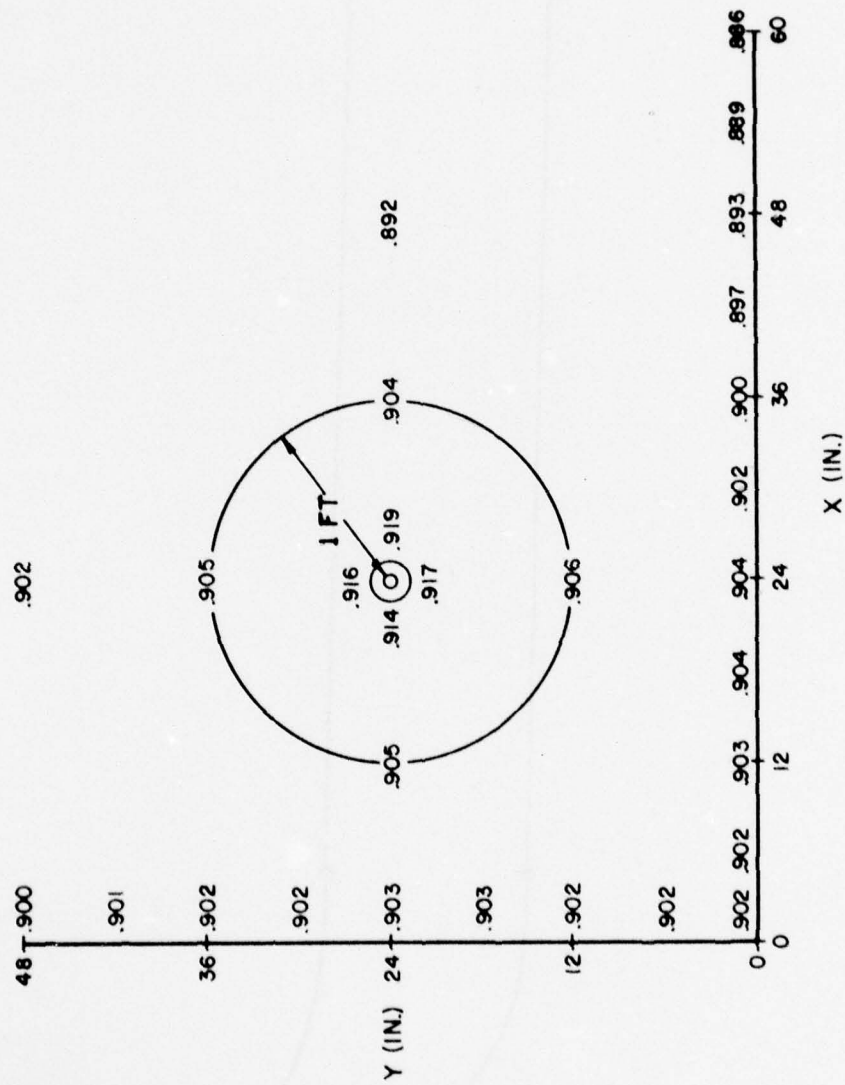


Figure 15. Protective plastic tube with 26.0 percent reduction in surface area.





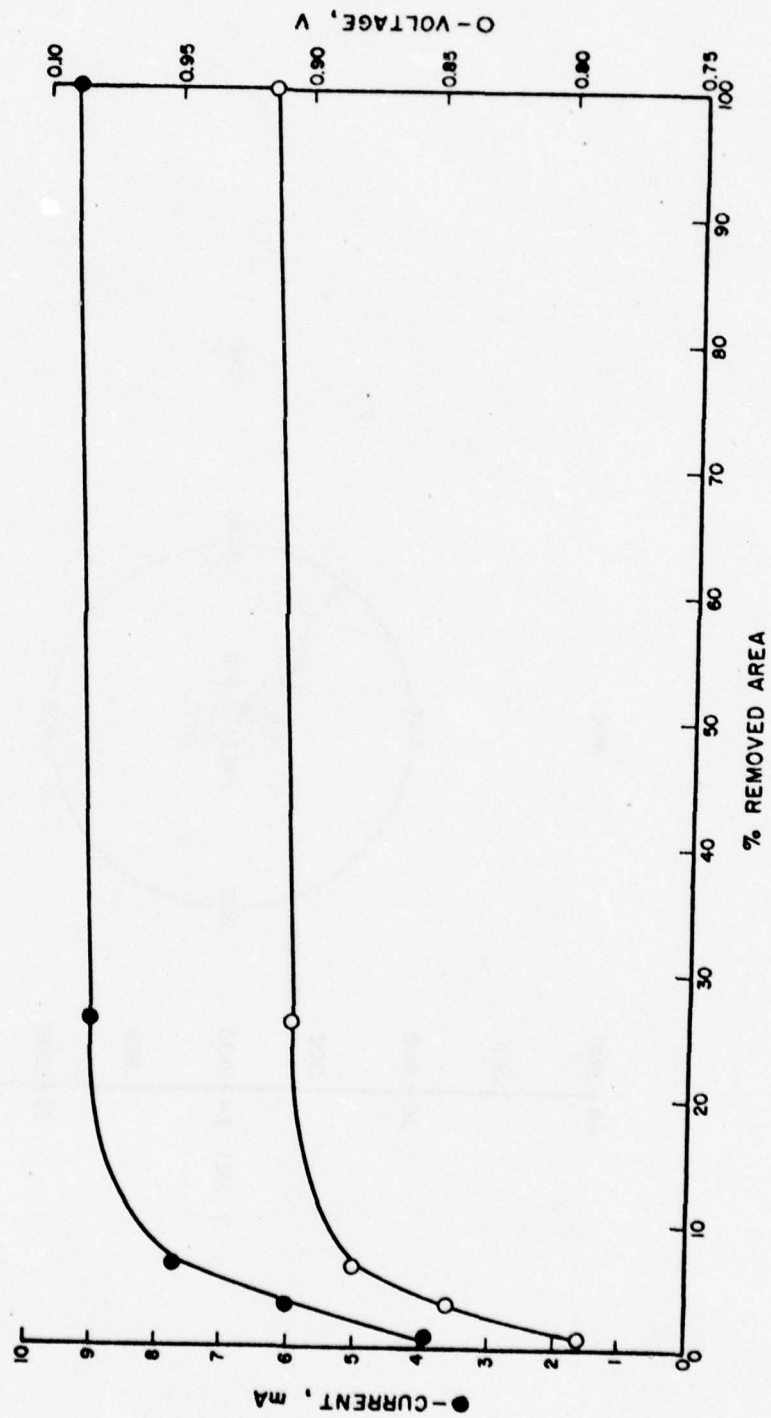


Figure 17. Current and voltage as a function of percent removed area.

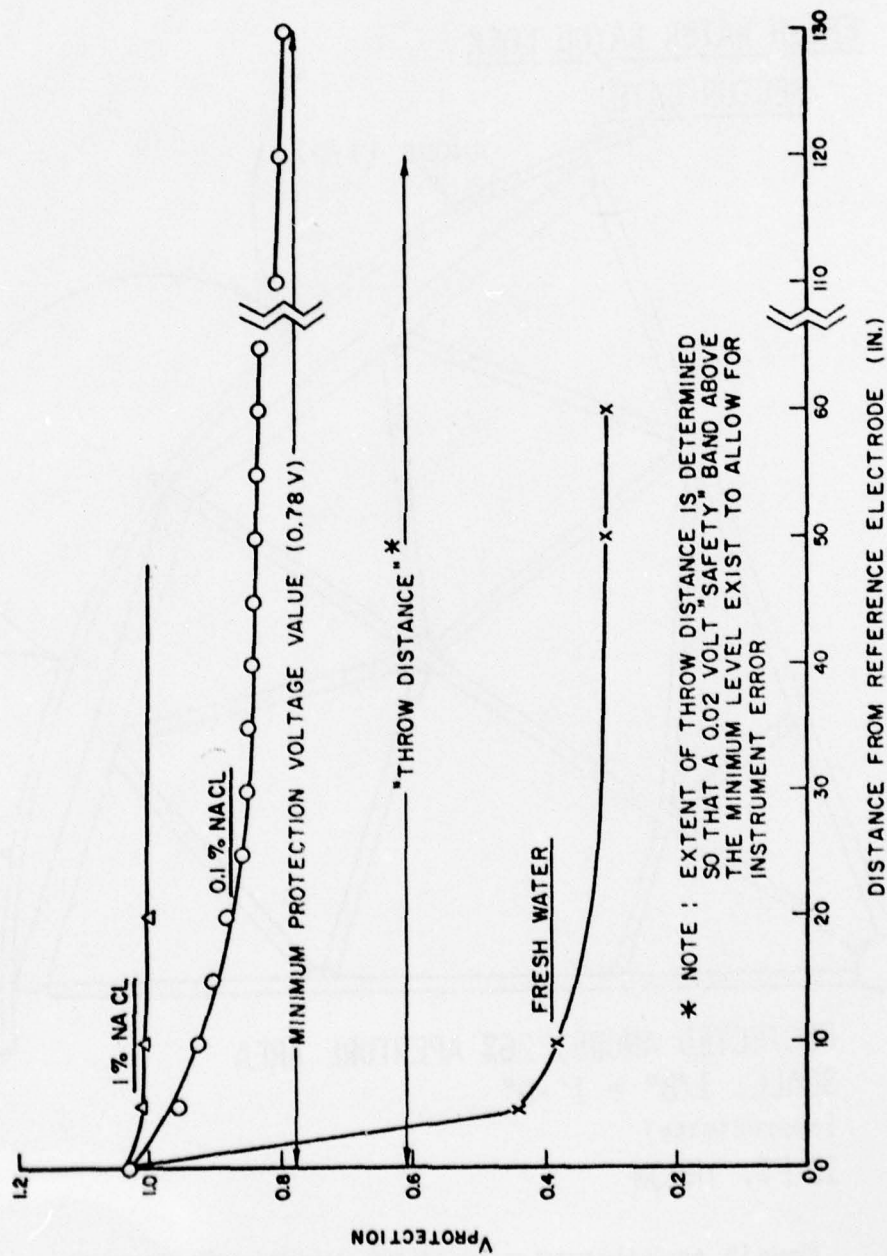


Figure 18. "Throw distance" for zinc anode for various water conditions (silver-silver chloride reference electrode at 0.1 percent sodium chloride solution). SI conversion factor: 1 in. = 25.4 mm.

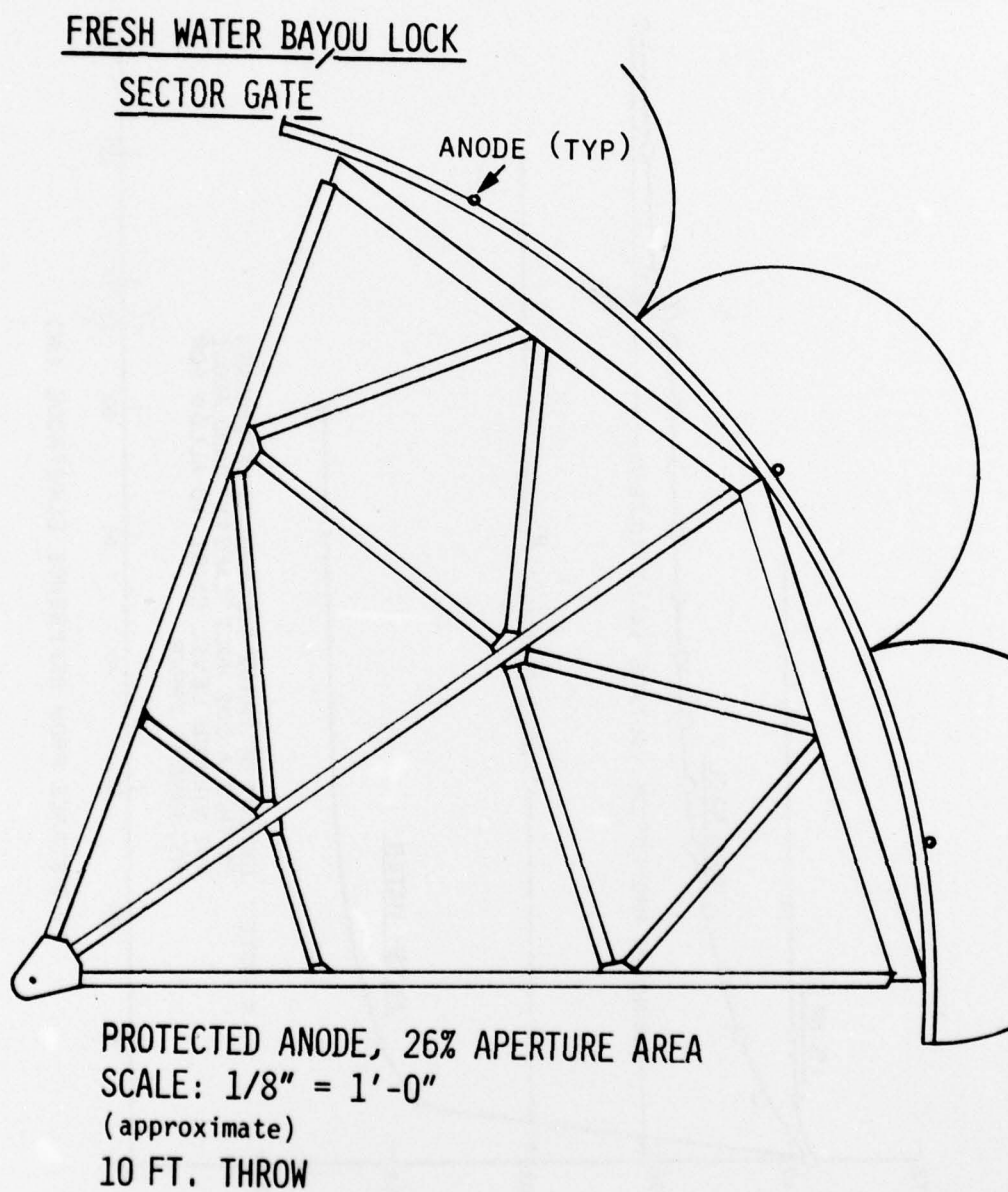
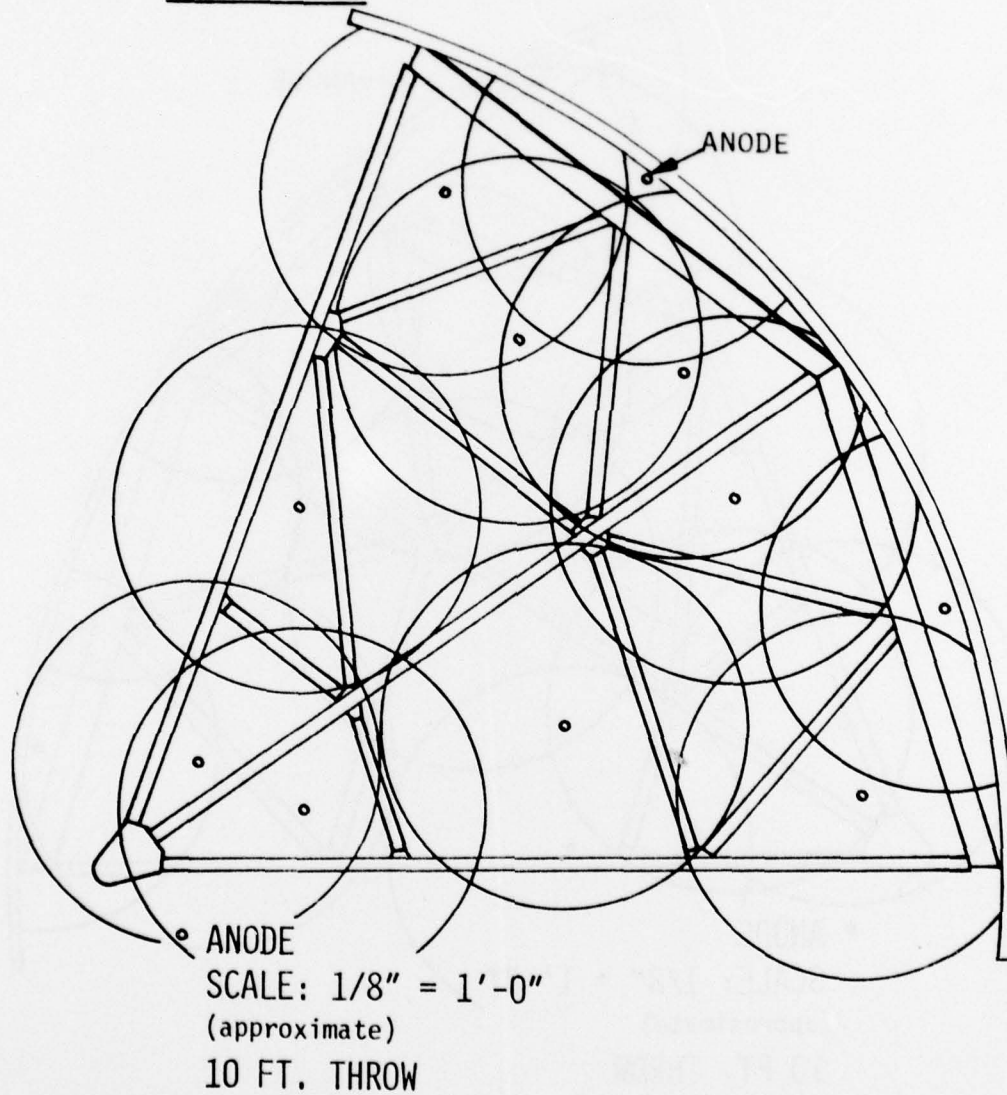


Figure 19. Anode placement on skin side with associated circles of protection.

FRESH WATER BAYOU LOCK

SECTOR GATE



**Figure 20.** Anode placement in chambers; anodes located in center of compartments with circles of protection.



FRESH WATER BAYOU LOCK

SECTOR GATE

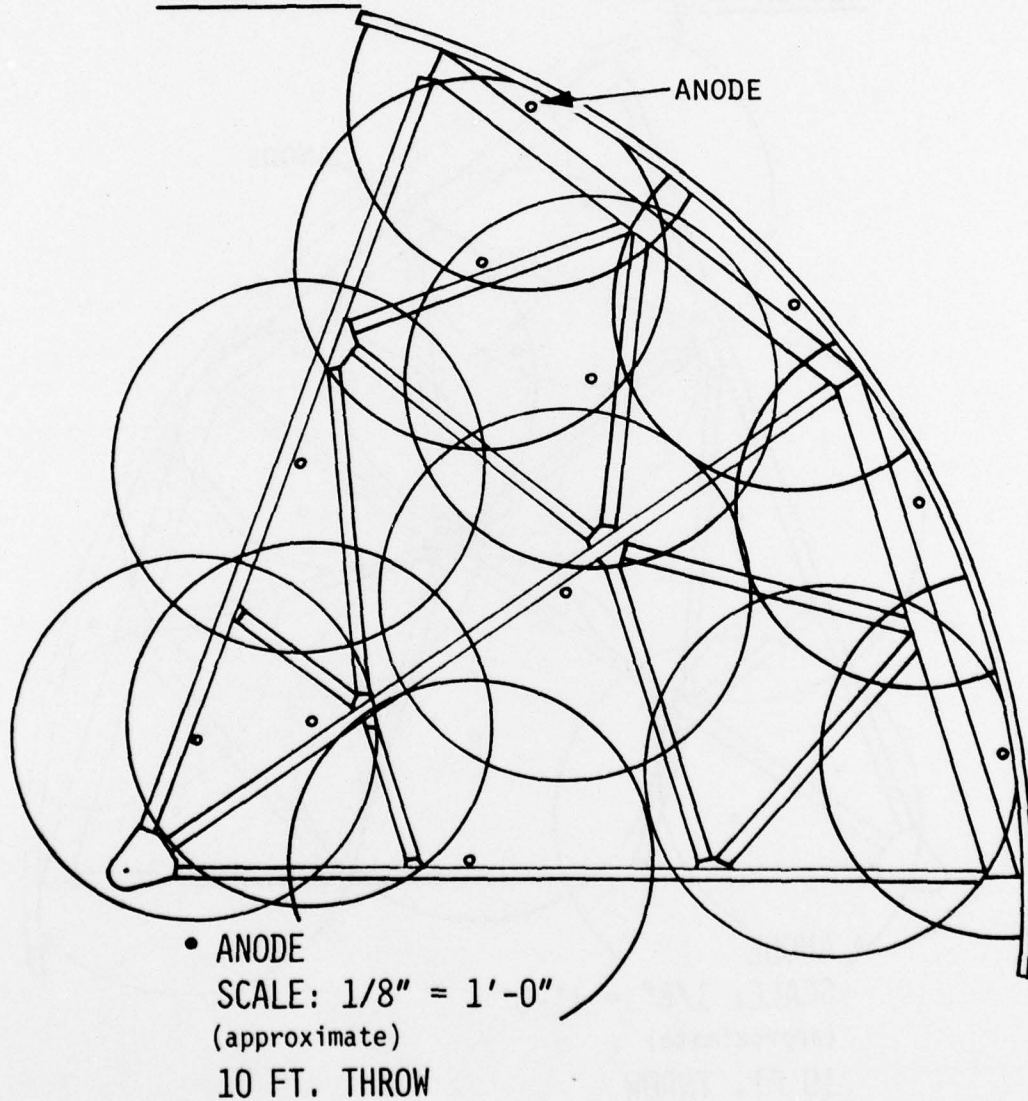
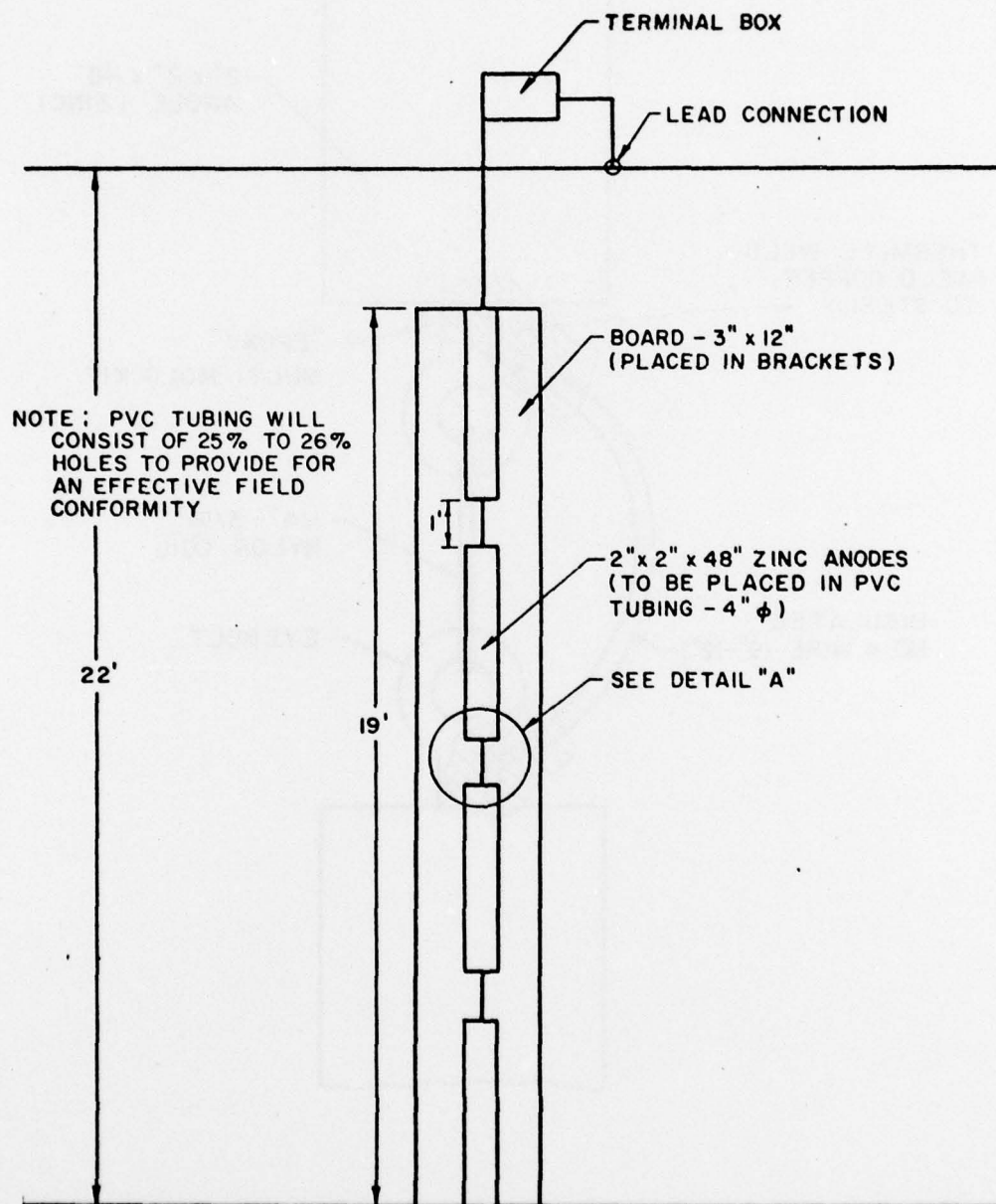
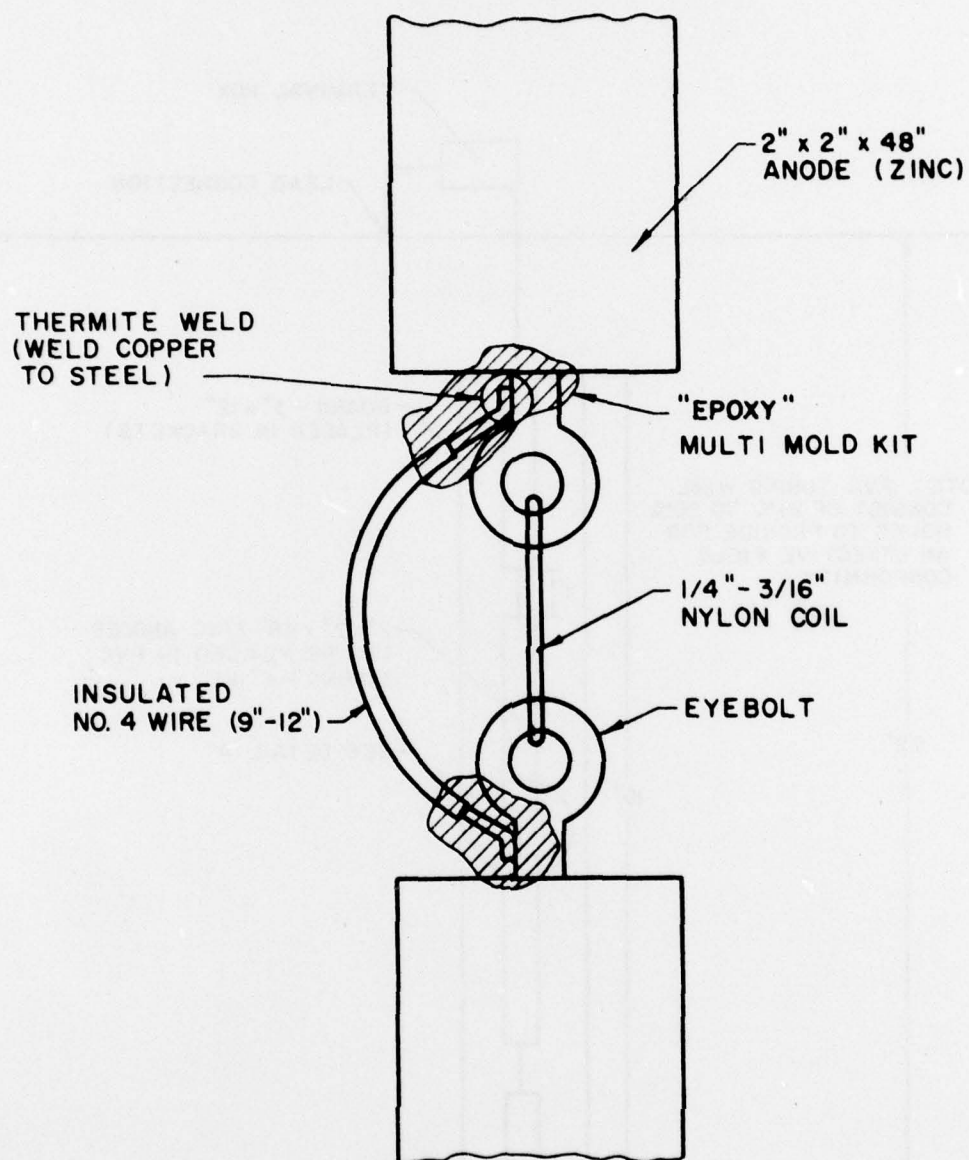


Figure 21. Anode placement in chambers; anodes relocated to mount on structural members.  
Circles of protection indicate all sections still adequately protected.



**Figure 22.** Layout of anode "string" for Fresh Water Bayou Lock.  
SI conversion factor: 1 in. = 25.4 mm.



DETAIL "A"

Figure 23. Detail of anode connection method for Fresh Water Bayou Lock cathodic protection system. SI conversion factor: 1 in. = 25.4 mm.

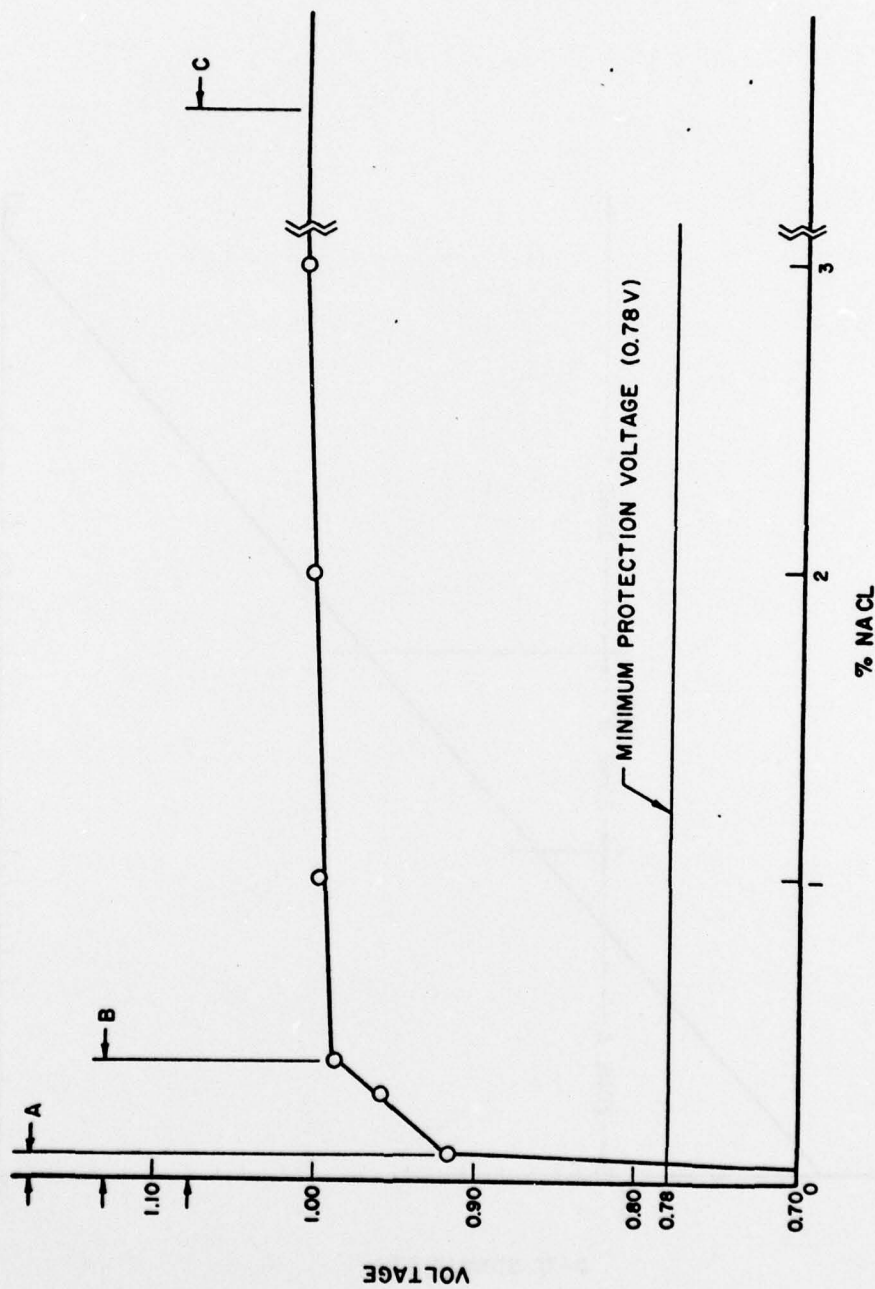


Figure 24. Brackish zones A, B, and C in relation to voltages at intersection point 2.8 ft (0.86 m) from the anode vs. percent sodium chloride.



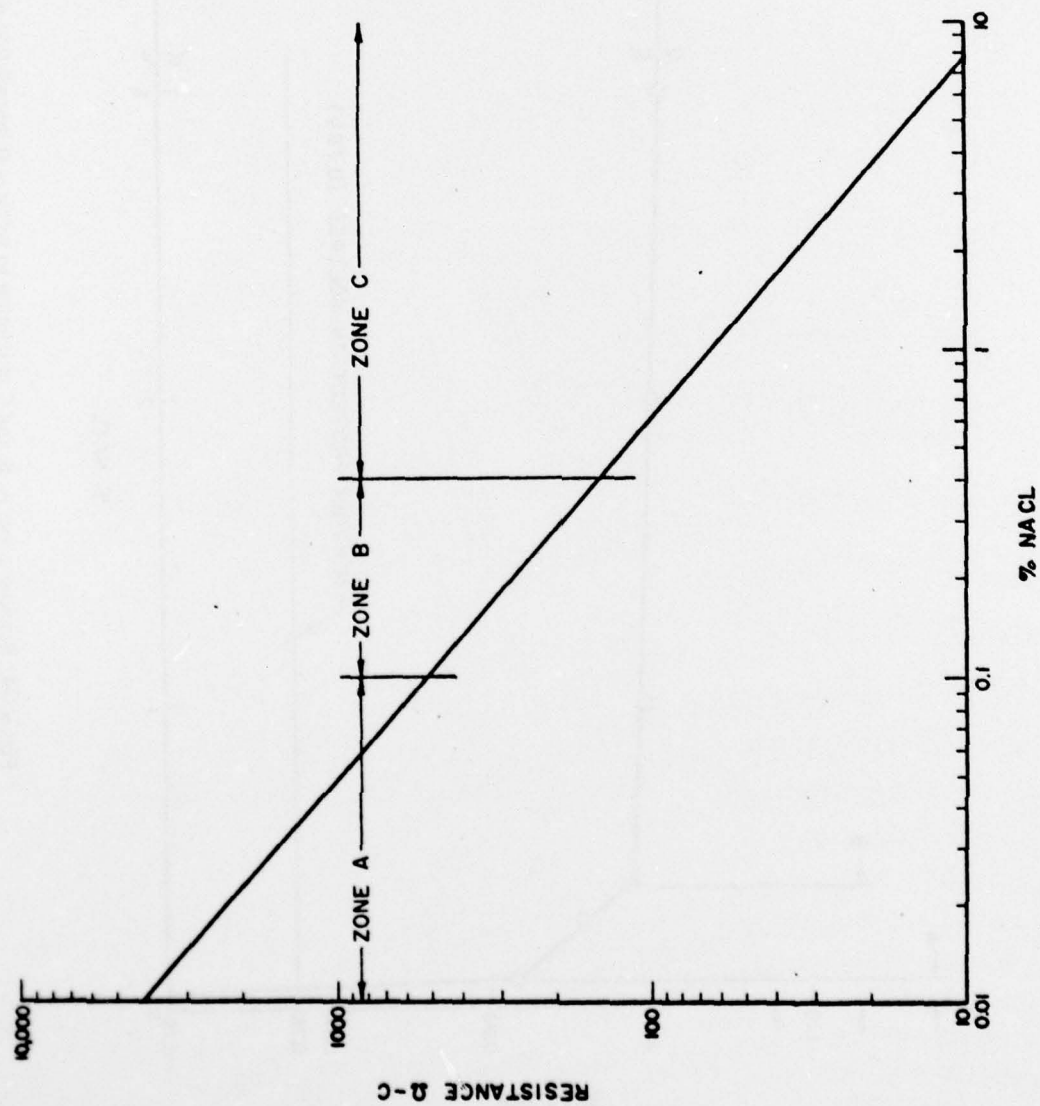


Figure 25. Conductivity vs. sodium chloride concentration with brackish zones indicated.

# **APPENDIX A:** **ANALYSIS OF CANAL WATER SAMPLE**

## **Qualitative Spectrochemical Analysis and Concentrational Estimates of Detected Constituents**

### **Sample Number: #1 Liquid**

Sodium	Major Constituent	
Magnesium, Calcium	2 - 20%	each
Potassium	0.5 - 5	
Strontium	0.05 - .5	
Boron	0.002 - .02	
Silicon	0.001 - .01	
Aluminum	0.0003 - .003	
Iron	0.0002 - .002	
Manganese, Copper	0.00005 - .0005	each
Titanium	T<0.001	
Chromium	T<0.0005	
Vanadium	T<0.0001	
Zirconium	ND<0.001	
Barium	ND<0.001	
Lead	ND<0.0005	
Nickel	ND<0.0003	
Cobalt	ND<0.0003	
Beryllium	ND<0.00005	
Silver	ND<0.00002	
Ash	0.71%	

### **Sample Number: #1 Solids**

Silicon	5 - 50%	
Aluminum	2 - 20	
Iron, Sodium	1 - 10	
Magnesium	0.5 - 5	
Potassium	0.3 - 3	
Titanium	0.2 - 2	
Calcium	0.05 - .5	
Manganese	0.02 - .2	
Strontium, Barium	0.01 - .1	each
Boron, Vanadium Zirconium, Chromium	0.005 - .05	each
Copper	0.001 - .01	
Lead, Nickel	0.0005 - .005	each
Cobalt	0.0003 - .003	
Beryllium	0.00003 - .0003	
Silver	0.00001 - .0001	
Ash	0.27%	

Analysis is based on the recovered ash.

T -- Trace  
ND -- Not Detected

## APPENDIX B: SAMPLE CALCULATIONS OF SACRIFICIAL ANODE REQUIREMENTS

A current density figure appropriate for a particular corrosion situation is commonly used to calculate the current required; for this application, the value of 10 mA/sq ft (108 mA/m<sup>2</sup>) was used. This value coupled with the years of life desired provides a figure for ampere-hours or ampere-years needed. The anode manufacturer's values for ampere-years per pound can then be used to obtain the total pounds of sacrificial anode required.

Sample calculations for the Fresh Water Bayou Lock are given below. The design procedures of TM 5-811-4, which is referenced in the computations, were used.

### Skin Side

Each sector gate skin is a cylindrical segment:

Circumferential segment length = 57 ft\*

Height = 16.5 ft

Area = 57 × 16.5 = 940.5 sq ft.

Assuming 20 percent coating "holidays" due to damage: 940.5 sq ft × 20 percent = 188.1 sq ft of bare (exposed) area that must be protected.

For a protective current density of 10 mA/sq ft, a total current of 1.88 A is required from the zinc anode (paragraph 7-07-a-1 of TM 5-811-4).

\*To avoid confusion, SI equivalents are not given in this example calculation. The applicable conversion factors are: 1 ft = 0.3048 m; 1 sq ft = 0.0929 m<sup>2</sup>; 1 in. = 25.4 mm; 1 lb = 0.4536 kg.

For this particular lock, the cycle for dewatering for refurbishing is 10 years. The weight of the anode required to supply the required current for the required period of time is determined by:

$$\text{Weight} = \frac{8760 \cdot Y \cdot I}{H \cdot F} (7-08-j-4)$$

where Y = life of anode (10 years)

I = current output (1.88 A)

H = amp-hr/lb for anode (372)

F = efficiency of anode (50 percent).

From this, the weight required is 886 lbs.

Using 2-in. × 2-in. × 48-in. zinc anodes weighing 50 lbs each gives a total requirement of 18 anodes. Figure 19 shows the distribution of these anodes.

### Chamber Side

Computing exact areas for the chambers is more difficult. However, since these sections of the gate are not as vulnerable to damage by barges, etc., emphasis should be on anode location to preclude lack of protection caused by shielding. Figure 5 illustrates distortion of the electric field which would shield a structural member.

After an approximate area of beams, gussets, etc., has been determined, the above anode requirement computations can be followed.

**APPENDIX C:  
REFERENCE ELECTRODE (HALF-CELL)  
CONVERSION DATA**

Corrosion engineers usually express corrosion potentials and cathodic protection voltage levels in terms of measurements made with a copper-copper sulphate half-cell. For measurements in brackish and saltwater electrolytes, this type of half-cell cannot be used be-

cause of cell contamination caused by electrolyte chloride ion migration through the permeable plug. In these situations, a silver-silver chloride half-cell is used; this type of half-cell results in a chloride ion equilibrium condition at the plug.

Because of the basic electrochemical differences between these cells, voltages measured by various half-cells differ. Table C1 provides equivalent values for the three most common cells with respect to the basic hydrogen cell.

**Table C1  
Electrode Conversion\***

Hydrogen (H <sub>2</sub> ) Electrode	Copper-Copper Sulfate (Cu-CuSO <sub>4</sub> ) Electrode	Silver-Silver Chloride (Ag-AgCl) Electrode	Calomel Electrode
0	+ .318	+ .250	+ .242
.1	.418	.350	.342
.2	.518	.450	.442
.3	.618	.550	.542
.4	.718	.650	.642
.5	.818	.750	.742
.6	.918	.850	.842
.7	1.018	.950	.942
.8	1.118	1.050	1.042
.9	1.218	1.150	1.142
1.0	1.318	1.250	1.242
.512	.830	.762	.754
.517	.835	.767	.759
.522	.840	.772	.764
.527	.845	.777	.769
.532	.850	.782	.774
.537	.855	.787	.779
.542	.860	.792	.784
.547	.865	.797	.789

\*Entries in each row are equivalent values obtained using the various electrodes. For example, a reading of .2 using a hydrogen electrode would be .518 using a copper-copper sulfate electrode; .450 using a silver-silver chloride electrode; and .442 using a calomel electrode.



## APPENDIX D: ECONOMIC CONSIDERATIONS IN CATHODIC PROTECTION DESIGN

In the design phase of the CP system for the Fresh Water Bayou Lock, specific elements were chosen from a variety of methods and materials that apparently are equally suitable to achieve the required corrosion control. The selection of a sacrificial anode method of CP is an example of a decision of this type, since an impressed-current system would have been as effective. This appendix presents some items to consider in developing a corrosion control system to obtain a cost-effective design; it is rudimentary, but should provide some overview of the economics involved. (A CERL draft report, *Economics of Corrosion Control Design for Civil Works*, is a more comprehensive and detailed dissertation.)

Coatings, in conjunction with cathodic protection, form a corrosion mitigation system; the coating is the primary protection with CP as the supplemental mechanism that protects exposed metal ("holidays") caused by progressive deterioration of the paint film or damage by impact of barges, debris, etc. Unfortunately, the corrosion mechanism associated with most of these holidays is insidious, since the localized corrosion cells formed are "autocatalytic" and the corrosion rate is increased by a factor of four or more.<sup>4</sup> The net result of such uncontrolled corrosion damage can be as serious as weld defects or casting inclusions. Thus, CP is a cost-effective corrosion control method for nearly all submerged waterways structures and should be required for water resistivity less than 10,000 ohm-cm and/or chloride content greater than 25 mg/l.

The technical aspects pertaining to the selection of CP type (sacrificial/impressed-current) are discussed in the introduction of this report; economic appraisals affecting final selection are structure-specific, and few generalizations can be formulated.

For large structures, impressed-current systems are usually less expensive than sacrificial systems since:

1. The area protected per anode is larger because higher CP voltage can be applied.

2. Anode cable runs are easily installed and not complicated by structure geometry.

3. Individual anode current can be separately adjusted by balance resistors for optimum protection. (In a sacrificial system such control is usually not possible and excessive anode consumption can occur.)

4. One rectifier can be used to energize several anodes; i.e., a single unit usually is sufficient to protect an entire mitre gate leaf.

For the Fresh Water Bayou Lock, the sacrificial system was chosen because:

1. The experimental work (electric field plots, etc.) showed that properly spaced zinc anodes operating in the conductivity variations anticipated would operate as discussed in Part 3 above.

2. The hostile atmospheric conditions (salt spray, heat, and high humidity) would require an oil-immersed rectifier and costly cable installations for an impressed-current system.

An analysis of the "as-built" cost of this sacrificial system shows that an impressed-current system would have increased the cost by 25 percent. Conversely, for the Algiers Lock in New Orleans, which is of a similar type and size and which is located in a more benign atmosphere and higher resistivity water, impressed current is more cost-effective.

Sacrificial anodes are particularly useful for gates and other structural components in confined spaces; in many instances, it is not possible to route anode leads for impressed current.

For supplemental "spot" protection or temporary CP, galvanic anodes usually are simplest and most economical.

It should be emphasized that the two types of CP systems are not mutually exclusive or incompatible. The prime objective in CP design is to provide the required protection voltage level, and a hybrid mix of galvanic and impressed-current anodes is accepted practice.

<sup>4</sup>Shreir, L. L., ed., *Corrosion* (John Wiley and Sons, Inc., 1973), pp. 1, 95.

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